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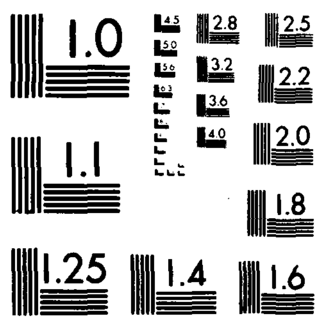

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SHEAR MODULI OF ORTHOTROPIC COMPOSITES

N. J. Pagano

Mechanics & Surface Interactions Branch
Nonmetallic Materials Division

March 1980

Technical Report AFML-TR-79-4164

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The elasticity solution for a circular cylindrical body possessing rectilinear orthotropy under pure torsion is used to define an experimental approach to determine the shear moduli of orthotropic composites. Attention is focused on the transverse shear modulus of a unidirectional composite, which is not routinely measured in the characterization procedure. This property, as well as the longitudinal shear modulus, can be determined from the same specimen, which consists of transversely oriented unidirectional fiber

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reinforcement. The simulation of the theoretical displacement boundary conditions and failure tests are also discussed.

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FOREWORD

This report was prepared by N. J. Pagano of the Mechanics and Surface Interactions Branch, Air Force Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio 45433. The work was initiated under Project No. 2419, Task No. 241903, Work Unit 24190310, WUD #45. The work covers research conducted during the period October 1978 to October 1979.

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SECTION I

INTRODUCTION

In many cases, all of the material properties that define the elastic response of a modern composite material have not been determined by experiment. For example, even the simplest unidirectional fiber reinforced composites, those possessing transverse isotropy, are not completely elastically characterized on a routine basis, as only four of the five required elastic constants are generally measured. Thus, consider a unidirectional composite reinforced by a hexagonal array of circular cylindrical fibers. Let the x axis coincide with the fiber direction and the numerical subscripts 1, 2, 3 stand for the x, y, z directions, respectively. The five independent elastic moduli can be represented by Young's moduli, E_{11}, E_{22}, Poisson ratio ν_{12}, and axial and transverse shear moduli, G_{12} and G_{23}, respectively. Only the first four of these are normally determined by test. These are sufficient to describe the plane stress response of thin sheets lying in planes parallel to xy, however, the fifth constant is needed to define the response of media in which interlaminar stresses are present.

In this work, we shall suggest an experiment which affords a direct determination of the transverse shear modulus, G_{23}. The approach utilizes pure torsion of a circular cylindrical body possessing rectilinear orthotropy. The effect of end attachments will also be treated.

The experimental method given here is sufficiently general to define the shear modulus of any orthotropic material in which one axis of elastic symmetry is aligned with the longitudinal axis of the cylinder, provided, of course, that a circular cylindrical specimen of the material can be prepared. The shear moduli of carbon-carbon materials utilized in the manufacture of reentry vehicle nose tips and rocket nozzle components can be evaluated in this manner. Such materials include reinforcement patterns consisting of three orthogonal sets of fibers or groups of fibers oriented parallel to the body diagonals of a prism or polygon.

Experimental measurements made through the use of the present approach are given by Huber (Reference 1).

SECTION II

ELASTICITY SOLUTION

Since our experiment depends upon the elasticity solution for an anisotropic circular cylinder under pure torsion, we shall discuss the pertinent details of the solution in this section. The problem was first solved by Saint-Venant (Reference 2) for an elliptical cylinder and is also treated by Lehknitskii (Reference 3).

Consider a circular cylindrical body reinforced by an array of parallel fibers* which are normal to the longitudinal axis. Without loss in generality, we can assume the fibers lie in the x-direction, as shown in Figure 1. Let the radius of the cylinder be designated by a and its length between end supports as ℓ, where the longitudinal coordinate z is in the range $0<z<\ell$. The body is subjected to a constant twisting moment T about the z-axis. We model the composite as a homogeneous, orthotropic cylinder represented by its effective moduli. Under the stated conditions, according to References 2, 3, the only non-vanishing stress and engineering strain components with respect to Cartesian coordinates x,y,z are τ_{xz}, τ_{yz} and γ_{xz}, γ_{yz}, respectively. Since τ_{xz} and τ_{yz} act in the planes of elastic symmetry, generalized Hooke's Law gives

$$\tau_{xz} = G_{12}\,\gamma_{xz}$$
$$\tau_{yz} = G_{23}\,\gamma_{yz} \qquad (1)$$

where G_{12} and G_{23} are the effective axial and transverse shear moduli, respectively. Furthermore, the elasticity solution yields the following stress distribution,

$$\tau_{xz} = -\frac{Ty}{J}$$
$$\tau_{xz} = \frac{Tx}{J} \qquad (2)$$

*As mentioned earlier, this particular fibrous structure is not essential to the present formulation. It is used here because of the importance of the definition of G_{23} in unidirectional composites.

where J is the polar moment of inertia of the cross-section about the z-axis, i.e., $J = \frac{\pi}{2} a^4$ for a circle. We observe that the stress distribution is the same as in an isotropic circular cylinder under torsion (however the strain distribution is different in the present case). The strain components can be found by substitution of Equation 2 into Equation 1, while integration of the strain-displacement relations of linear elasticity leads to the following displacement field,

$$\begin{aligned} u &= -\alpha yz + c_1 y + c_2 z + c_3 \\ v &= \alpha xz - c_1 x + c_4 z + c_5 \\ w &= Qxy - c_2 x - c_4 y + c_6 \end{aligned} \tag{3}$$

where u,v,w are the x,y,z components of displacement, respectively, α is the angle of twist per unit length defined by

$$\alpha = \frac{T}{2J}\left(\frac{1}{G_{23}} + \frac{1}{G_{12}}\right) \tag{4}$$

and

$$Q = \frac{T}{2J}\left(\frac{1}{G_{23}} - \frac{1}{G_{12}}\right) \tag{5}$$

The various constants c_1 --- c_6 in Equation 3 represent rigid body motion. Owing to displacements prescribed in the next section, they all vanish. Finally, it is more instructive to express the solution in terms of cylindrical coordinates, r,θ,z where

$$\begin{aligned} x &= r \cos\theta \\ y &= r \sin\theta \end{aligned} \tag{6}$$

Hence, applying standard transformation equations we get the following stresses,

$$\tau_{z\theta} = \frac{Tr}{J}, \quad \tau_{rz} = 0 \tag{7}$$

strains,

$$\gamma_{z\theta} = \frac{Tr}{J}\left(\frac{\sin^2\theta}{G_{12}} + \frac{\cos^2\theta}{G_{23}}\right)$$

$$\gamma_{rz} = \frac{Tr}{J}\left(\frac{1}{G_{23}} - \frac{1}{G_{12}}\right) \sin\theta \cos\theta \tag{8}$$

and displacements,

$$u_r = 0$$

$$u_\theta = \alpha rz \tag{9}$$

$$w = Qr^2 \sin\theta \cos\theta$$

Since u_r vanishes, there is no change in the radius of the cylinder after the torque is applied, however, the longitudinal displacement w is non-zero. Consequently, warping occurs.

SECTION III

END CONDITIONS

Owing to the existence of warping, care must be exercised in designing a proper device for load introduction in this experiment, i.e., we must ensure that the displacement field given by Equation 9 is, in fact, present throughout the specimen, or at least in a gage section. For example, if the ends of the specimen are completely clamped, extraneous bending, of the type described by Pagano and Halpin (Reference 4) may occur. In order to minimize the influence of end constraint, we can support the specimen as shown in Figure 1, by small rods at the 8 points having x,y coordinates (0, ±a) and (±a, 0) at $z = 0,\ell$. For, if we assume that the end $z = \ell$ is rotated while the $z = 0$ is stationary, the displacements must satisfy the following conditions at $\theta = 0,\ \pi/2,\ \pi,\ 3/2\pi$:

$$u_r = u_\theta = w = 0 \quad \text{at} \quad r = a,\ z = 0 \tag{10}$$

and

$$u_r = w = 0,\ u_\theta = \alpha\ell a \quad \text{at} \quad r = a,\ z = \ell \tag{11}$$

Clearly, the displacement field given by Equation 9 satisfies all the conditions of Equations 10 and 11. Therefore, application of Saint-Venant's principle suggests that, away from the ends, the response is given by Equations 7, 8, and 9. In the limiting case where $G_{23} = G_{12}$, the strain and displacement fields are given by the usual isotropic torsion formulation, although the material need not be isotropic. Thus for orthotropic materials in which $G_{23} = G_{12}$, clamped ends are appropriate. Experimental work by Huber (Reference 1) has shown that the influence of a clamped end is small for a composite in which G_{23} and G_{12} differ slightly. However, the general severity of this effect is unknown at this time.

SECTION IV

EXPERIMENTAL MEASUREMENTS

The experimental determination of G_{23} follows for the measurement of $\gamma_{z\theta}$ on the surface near the central plane $z = \ell/2$ at either $\theta = 0$ or $\theta = \pi$ and applying the first of Equations 8. Note that $\theta = 0, \pi$ correspond to the fiber direction in this specimen. This experiment can also serve as a means of evaluating the axial shear modulus, G_{12}. In this case, one can measure the surface shear strain at $\theta = \pi/2$ or $\theta = 3/2\pi$ and again apply the first of Equation 8. Thus we have

$$G_{23} = \frac{Ta}{J\gamma_{z\theta}(a,o)} \tag{12}$$

and

$$G_{12} = \frac{Ta}{J\gamma_{z\theta}(a, \pi/2)} \tag{13}$$

where, for example, $\gamma_{z\theta}(a,o)$ is evaluated at $r = a$, $\theta = 0$. Since $\varepsilon_z = \varepsilon_\theta = 0$ in the specimen, the shear strain $\gamma_{z\theta}$ at a point on the surface is equal in magnitude to twice the normal strain at 45° to the longitudinal axis at the same point. Thus, a single element strain gage suffices to determine $\gamma_{z\theta}$. It is important to observe, however, that, unlike the torsion of an isotropic cylinder, $\gamma_{z\theta}$ in the present experiment is a function of θ. Hence, errors in positioning the strain gage, as well as its misalignment, may affect the accuracy of the experiment. Furthermore, the strain varies over the length of the strain gage. Errors due to the position of the strain gage and corrections for the length of the gage, however, can be estimated from the first of Equations 8, in conjunction with two observed values of $\gamma_{z\theta}$. The difference in the θ coordinate of the ends of a 45° strain gage element is given by

$$\Delta\theta = \frac{b}{\sqrt{2}a} \tag{14}$$

where b is the length of the strain gage element and $\Delta\theta$ is expressed in radians. The effect of gage misalignment can be estimated from the standard transformation of strain equations along with the first of Equations 8.

SECTION V

SHEAR STRENGTH

The shear stress in a solid circular cylindrical rod varies according to Equation 7 within the elastic range of the material. Hence, the present test is not optimum for the determination of shear strength. The undesirable stress gradient may be reduced by coring out the center of the rod, thus producing a hollow cylindrical specimen.

While stress gradients can be controlled in this manner, the failure mode is governed by material properties. As tensile and compressive stresses equal in magnitude to $\tau_{z\theta}$ exist, non-shear failure is possible, in fact, probable for unidirectional composites (Reference 5), where transverse tension may control the failure mode. In such cases, only a lower bound shear strength is given. A combined loading condition would be required to produce a true shear failure. Failure occurring in the plane $\theta = 0$ is associated with the ultimate value of τ_{23}. Failure occurring in a plane z = const., however, is somewhat ambiguous as both τ_{12} and τ_{23} act in this plane and are of equal magnitudes. Hence, the precise shear strength component being determined in the latter case is not clear.

SECTION VI

CONCLUSIONS

We have proposed an experimental approach to define the shear moduli of orthotropic materials. Of particular interest is the capability to determine the transverse shear modulus of unidirectional composites. The specimen discussed is a circular cylinder reinforced by fibers in the direction of one diameter (in the case of unidirectional composites). The elasticity solution for the torsional response of such a body leads to the identical stress field that exists in isotropic cylinders, however, the strain and displacement fields differ from their elementary counterparts. The analysis shows that both G_{23} and G_{12} can be determined by suitable placement of single element strain gages. It is also possible to simulate the theoretical displacement boundary conditions.

The use of hollow cylinders is proposed for strength determination, however, non-shear failure modes are probable. Therefore combined loadings may be required in the definition of shear strength.

The experimental issues associated with this test method are treated by Huber (Reference 1).

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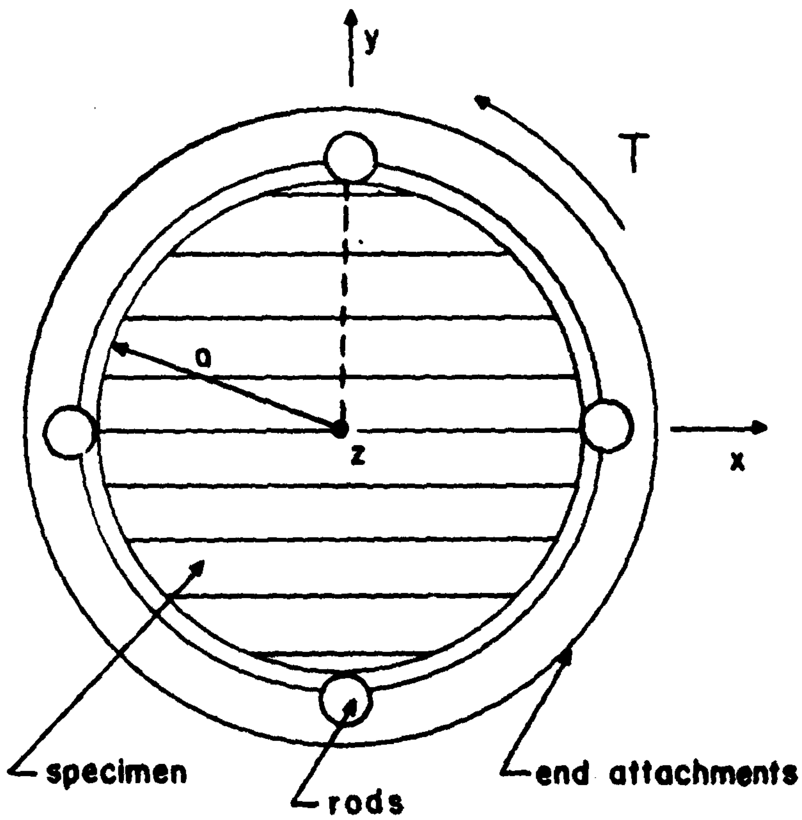

Figure 1. End View of Torsion Specimen

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